

# VACUUM PLASMA SPRAY (VPS) FORMING OF SOLAR THERMAL PROPULSION COMPONENTS USING REFRACTORY METALS

**Frank R. Zimmerman,**  
**David A. Hissam,**  
**Harold P. Gerrish**  
 NASA, Marshall Space Flight Center  
 Marshall Space Flight Center, Alabama, 35812  
 256-544-4958

**William M. Davis**  
 Boeing North America  
 Rocketdyne Division  
 555 Discovery Dr. #1, MS RA-02  
 Huntsville, Alabama, 35806-2809  
 256-544-2738

## ABSTRACT

The Thermal Spray Laboratory at NASA's Marshall Space Flight Center has developed and demonstrated a fabrication technique using Vacuum Plasma Spray (VPS) to form structural components from a tungsten/rhenium alloy. The components were assembled into an absorber cavity for a fully-functioning, ground test unit of a solar thermal propulsion engine. The VPS process deposits refractory metal onto a graphite mandrel of the desired shape. The mandrel acts as a male mold, forming the required contour and dimensions of the inside surface of the deposit. Tungsten and tungsten/25% rhenium were used in the development and production of several absorber cavity components. These materials were selected for their high temperature ( $>2500^{\circ}\text{C}$  [ $>4530^{\circ}\text{F}$ ]) strength. Each absorber cavity comprises 3 coaxial shells with two, double-helical flow passages through which the propellant gas flows. This paper describes the processing techniques, design considerations, and process development associated with forming these engine components.

## NOMENCLATURE

GEO	Geosynchronous Earth Orbit
$I_{sp}$	specific impulse (thrust per propellant weight $\times \text{sec}^{-1}$ )
LEO	Low Earth Orbit
N	Newtons
VPS	Vacuum Plasma Spray
kPa	kilopascals
$lb_f$	pounds force
$lb_m$	pounds mass

## INTRODUCTION

NASA's interest in Solar Thermal Propulsion is largely for boosting future payloads from low earth orbit (LEO) to geosynchronous orbit (GEO) or other high orbits. In the more distant future, low cost propulsion will be needed for interplanetary or solar exploration and observation. The state of the art is chemical propulsion (solid or liquid fuel). While these systems provide high thrust, are well understood and fairly reliable, they are limited by their complexity and low specific impulse ( $I_{sp}$ ). They tend to be more massive and complex,

particularly liquid fuel systems.

Other, more advanced propulsion concepts overcome these limitations, but often with other considerations that make them less attractive. For example, electric propulsion provides up to ten times the  $I_{sp}$  of current chemical systems, but at very low ( $\sim 2.2\text{ N}$  [ $0.5\text{ lb}_f$ ]) thrust. This results in LEO to GEO that require months rather than days. Nuclear propulsion can provide high thrust and  $I_{sp}$ , which would shorten travel time while lowering propellant requirement. However, safety and environmental issues are substantial, and current political considerations eliminate the possibility of serious development work.

Solar thermal propulsion offers a useful compromise among these considerations. It can provide higher  $I_{sp}$  than chemical systems, and higher thrust to weight ratios than electrical system. Because it is not a combustion process, solar thermal propulsion only requires one propellant gas, and combines moderate thrust ( $<445\text{ N}$  [ $<100\text{ lb}_f$ ]) with moderate propellant efficiency ( $860\text{ sec } I_{sp}$ ). This results in a boost time from LEO to GEO of about 30 days, which is acceptable for many applications. For more distant travel, a solar thermal engine would function much like a simple, efficient tug boat in space.

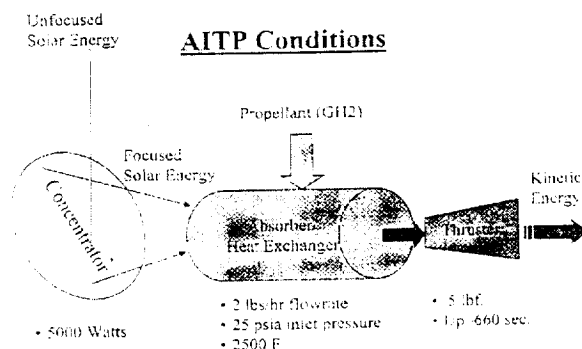


Figure 1. Schematic of AITP Solar Thermal Engine.

In the operation of a solar thermal engine, the absorber functions as a heat exchanger (Figure 1). Sunlight is concentrated with a lens or mirror, and focused into the absorber, raising the temperature to over 2500° C (4530° F). The absorber cavity produced at MSFC comprises 3 VPS-formed coaxial shells with two, double-helical flow passages through which the propellant gas flows. As the gas flows through the helical channels, it absorbs energy, expands and exits the nozzle. Through this process, solar energy is converted to kinetic energy and thrust. The test units built at MSFC are designed to produce 2 to 2.5 N (0.5 to 0.6 lb.) of thrust using hydrogen as the propellant. The intended service temperature of the ground test absorber cavity is 2125° C (3860° F), with an internal gas pressure of 170 kPa (560 psi), using hydrogen as the working fluid.

### APPROACH

The objective of this program was to first produce a proof-of-concept absorber, made of tungsten, to demonstrate the vacuum plasma spray (VPS) process. Tungsten was used to form these demonstration shells because the powder stock was relatively inexpensive and available from a local producer, in Madison, Alabama. Each lot of powder received for vacuum plasma spray forming is evaluated for particle size and distribution using a wet particle analyzer. A scanning electron microscope is used to evaluate particle morphology. The tungsten and molybdenum powders exhibited the same angular morphology as seen in Figure 2. Typical size range of these particles is 5 to 45 microns.

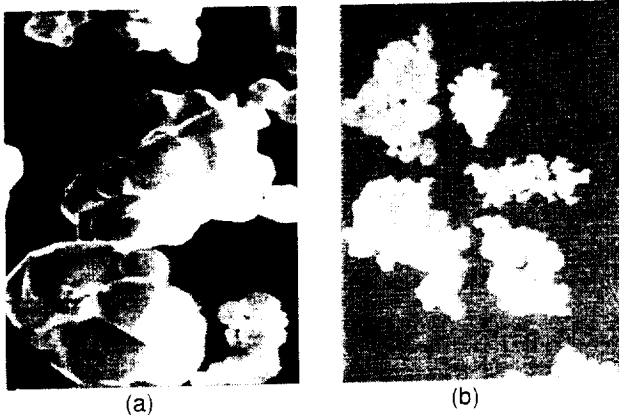
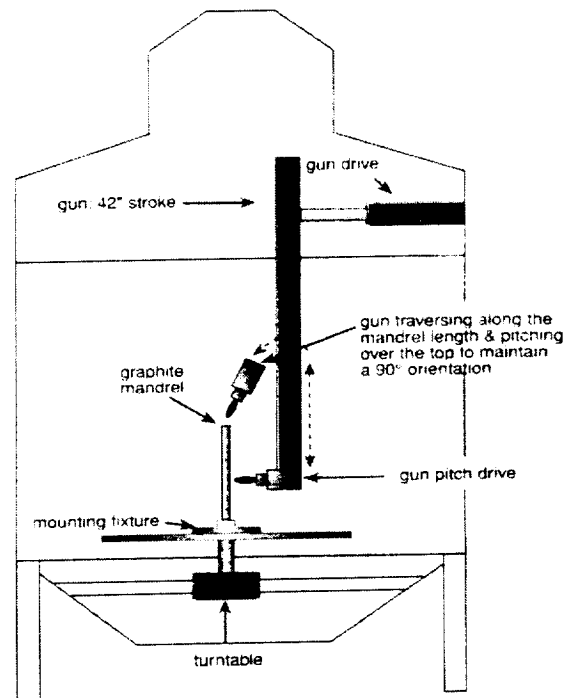


Figure 2. SEM photograph of (a) tungsten powder, (b) tungsten-25% rhenium powder.

VPS is a thermal spray process conducted in a low-pressure, inert atmosphere within a vacuum chamber. A 100 kW (95 Btu/sec) plasma is generated by passing an argon/hydrogen gas mixture through a DC arc. The gas is ionized, and the resulting high-temperature plasma exits through a nozzle into the low pressure (nominally 13 kPa [1.9 psi] ) argon environment. The material to be deposited is injected into the plasma plume as a fine powder, heated, and accelerated toward the substrate to be coated. The torch motion is computer controlled with 3 axes of motion available.

Initial plasma spray parameters were developed on flat steel plates mounted vertically in a fixture. Part temperature was monitored constantly by a dual wavelength pyrometer. The microstructures of the deposited material were evaluated for grain size, structure, and homogeneity. The density of the deposit was measured using a computer image analyzer. Spray parameters and torch motion were adjusted based on the results. Parameters established using these steel plates were then applied to the graphite mandrels.

To form the shells for the absorber cavity, tungsten was deposited in layers on a graphite mandrel. During VPS forming, the mandrel functions as a male mold, with the outer contour of the mandrel forming the inside contour of the sprayed deposit. These mandrels are rotated about their vertical axis by a turn table while the plasma torch traverses up and down. The plasma torch was pitched from a horizontal spray axis to nearly vertical in order to coat the closed, hemispherical end of the mandrel. Figure 3 shows the arrangement of the mandrel and plasma torch within the VPS chamber.



Vacuum Plasma Spray Facility

Figure 3. Arrangement of the mandrel and plasma torch within the VPS chamber. Notice the position of the torch as it pitches around the top of the mandrel.

For the demonstration unit, two shells were fabricated to form an absorber. The first was a simple "test tube" shape, with the open end serving as an aperture for the focused sun light. This inner shell functions as a black body absorber, trapping the energy of the directed light. The second, outer shell was more complex. It consisted of double helix threads on the side walls of a tube, and a converging-diverging nozzle formed on one end. The inside diameter of the thread valleys were matched by

grinding the outside diameter of the smooth wall test tube shell. Thus when the smaller, smooth wall shell is placed coaxially, into the larger helical shell, a continuous flow path is formed between the two shells, which exits from the nozzle. A seal ring is then brazed on to the open ends of the shells to seal the gas path while leaving the aperture open.

To form the shell, mandrels had to be fabricated from material that would withstand the high temperatures of vacuum plasma spray, not adhere to the tungsten, not cause any undesirable reactions, and have a compatible coefficient of thermal expansion. In addition, the mandrel had to be easily machined into the desired shape. A high expansion grade of graphite was selected as the mandrel material because it was demonstrated to be stable at the high spray temperature and could withstand the high thermal gradients imposed by the plasma. The graphite would not metallurgically bond to the sprayed tungsten, allowing the coating to be pulled off the mandrel after spraying. High expansion graphite eased removal of the shell by shrinking at a greater rate than the tungsten as the system cools.

Fabrication of the outer shell was more complex because of the helical walls. Since the tungsten coating was "locked" into the mandrel, unequal expansion of the mandrel with respect to the coating due to differing coefficients of thermal expansion (CTE) would crack the tungsten deposit. A grade of graphite was found that closely matched the CTE of the tungsten. This allowed the deposit to shrink at the same rate as the mandrel as they cooled. However the mandrel had to be machined out for removal, so they could only be used one time, while the smooth inner shell's mandrel was used several times.

Fabrication of the proof-of-concept unit demonstrated the feasibility of this approach. The second objective of this program was to produce an absorber to be used for ground testing. This absorber was similar in configuration to the demonstration unit, but it comprised three coaxial shells. This provides two independent flow paths, one on either side of the helical shell. For the ground test shell, a tungsten-25%rhenium alloy was selected. This alloy is substantially more ductile than the pure tungsten. It also provides a slight improvement in high temperature strength. Two sets of three shells each were fabricated and assembled into two absorbers for ground testing.

## RESULTS

Tungsten powder was sprayed on graphite mandrels to a nominal thickness of 1.65 mm (0.065 inch). Full size mandrels measured 457 mm (18 inches) long by 64 mm (2.5 inch) in diameter. After tungsten was sprayed on the mandrels, they were cross sectioned, mounted, and metallurgically examined. It was found that the tungsten density varied from 85% to 97%, depending on the part of the mandrel from which the sample was removed. The as-sprayed microstructure exhibited a strong dependence on the substrate temperature during deposition. Tungsten deposited on substrates at 815°C (1500°F) or below resulted in a splat-like, lamellae structure as seen in Figure 4.

Powder particle solidification at the high substrate temperatures combined with recrystallization and grain growth increased the tungsten density to 99% (Figure 5). After evaluation of several tungsten sprayed specimens, a transition

temperature range of 925° - 1090°C (1700° - 2000°F) was found where recrystallization began on some, but not all specimens.

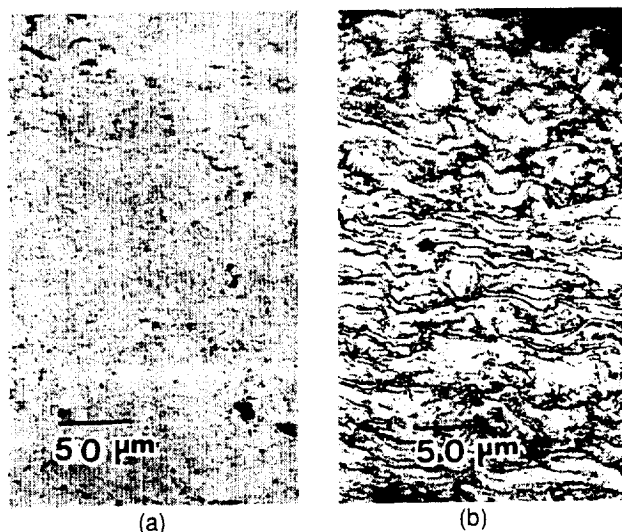


Figure 4. VPS tungsten microstructure as deposited on substrates below 815°C (1500°F) is typical of a dense splat structure, magnification 200x, (a) as polished, (b) etched with Murakami's Reagent (modified).

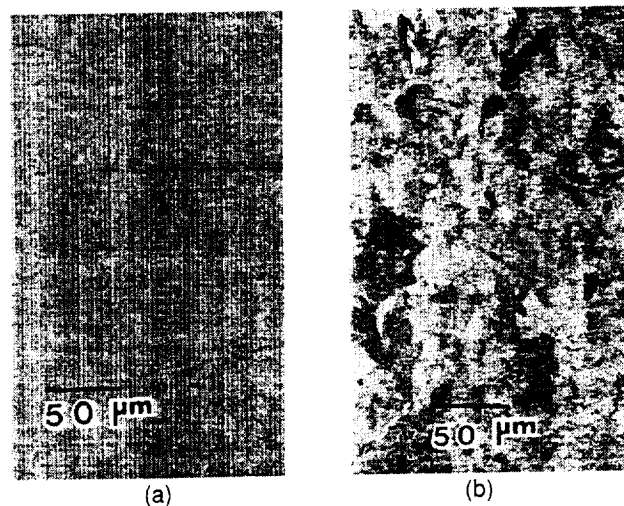


Figure 5. VPS tungsten microstructure as deposited on substrates above 1150°C (2100°F) with a dense, partially recrystallized microstructure, magnification 200x, (a) as polished, (b) etched with Murakami's Reagent (modified).

Tungsten and molybdenum have been formed into free standing cartridges using the vacuum plasma spray process. As deposited tungsten can be sprayed up to 97% dense in a splat structure and 99% dense in a recrystallized structure. The microstructure varied from a splat structure to a recrystallized structure depending on the substrate spray temperature. Tungsten powder deposited below 815°C (1500°F) showed no

signs of recrystallization. In-situ recrystallization of the VPS tungsten occurred at temperatures above 1150°C (2100°F) while material deposited between 815-1150°C (1500-2100°F) exhibited only sporadic recrystallization.

The higher deposition temperatures induced recrystallization of the tungsten, producing a more dense, homogeneous product. Metallographic analysis showed that prior powder particle boundaries were consumed during recrystallization. Past experience has demonstrated that the recrystallization and grain growth beyond prior particle boundaries increases elevated temperature strength and ductility.<sup>4,5</sup>

The hardness of the as-sprayed tungsten required the use of ceramic cutters. The lathe operation was performed without coolant (dry) and yielded a good surface finish. Unfortunately the brittle cutters often shattered as they dug in to occasional "soft spots" in the material. Diamond impregnated grinding wheels were successfully used on later samples, and provided an excellent surface finish on the tungsten and tungsten-25%rhenium shells. All machining and grinding was performed on the outside diameter of the shells.

The proof-of-concept absorber (two shells) was used to successfully demonstrate VPS forming, mandrel extraction, machining, and fabrication (Figure 6). Upon completion, it served as a bench test unit for instrumentation and testing techniques that would later be used on the ground test (three shells) absorbers.

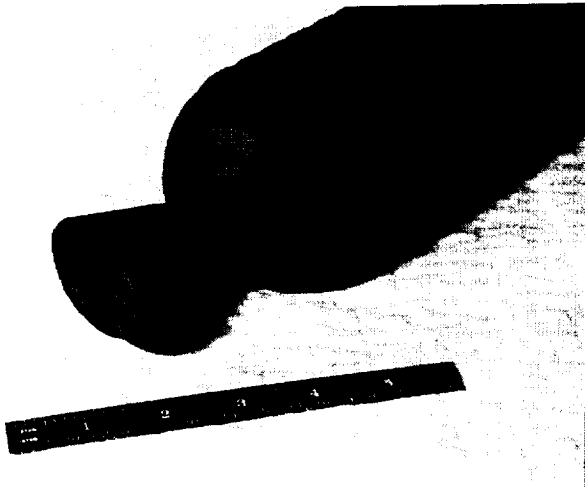


Figure 6. Nozzle and helical flow path on outer shell of proof-of-concept absorber.

The three shell ground test absorber (Figures 7 and 8) was installed and tested at the Air Force Research Laboratory's (AFRL) Solar Laboratory in California. The objective of this effort was to test the entire system. Only the results of the solar absorber thruster are presented in this paper.

The tungsten-25% rhenium absorber was loaded into a support structure, then enclosed in insulating material. The unit was placed inside the AFRL test chamber in a low ambient pressure of helium. Hydrogen propellant flowed at a rate of 1.8 kg/hr (4 lb<sub>m</sub>/hr) through the absorber. Due to weather conditions

and some system limitations, such as the inefficient solar collector, a relatively low solar flux of 800 W/m<sup>2</sup> (254 Btu/hr ft<sup>2</sup>) was provided to the absorber. This produced a measured thrust of 1.6 N (0.36 lb<sub>f</sub>) and I<sub>sp</sub> of 325 seconds during the 4 hour test. The absorber performed as designed, with no damage or leaking observed.

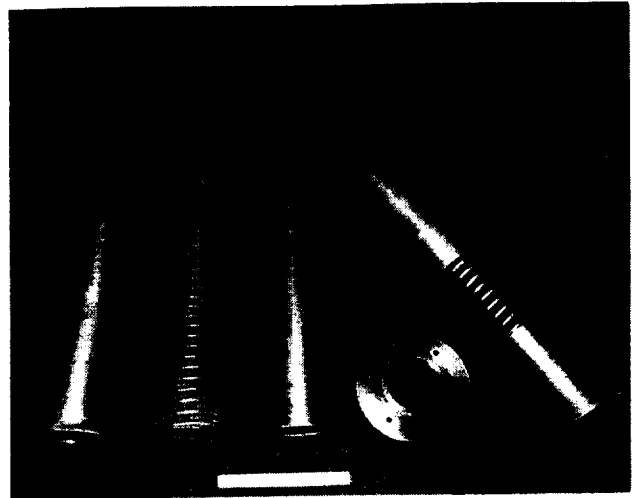


Figure 7. Three-shell absorber cavities. Individual shells are shown on the left, partially assembled absorber on the right.

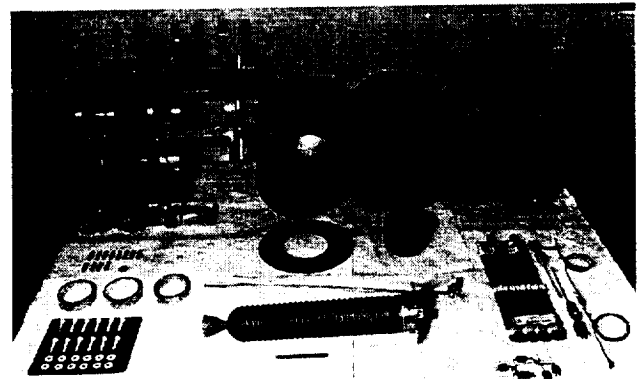


Figure 8. AITP Engine Assembly. Absorber cavity shown in the middle, bottom, with support structure, insulation, and instrumentation for ground test.

## CONCLUSIONS

1. Tungsten and tungsten-25%rhenium can be formed into free-standing structures with densities up to 97% and assembled into solar thermal absorbers.

2. VPS tungsten microstructure is dependent on substrate temperature. Material deposited below 815°C (1500°F) displayed a splat structure while material deposited above 1150°C (2100°F) was recrystallized.

3. VPS-formed tungsten-25%rhenium absorber shells will function properly and without material degradation during ground

testing as part of a solar thermal propulsion system.

#### ACKNOWLEDGMENTS

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